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(54) **CONTROLLING POWER FACTOR IN A SWITCHING POWER CONVERTER OPERATING IN DISCONTINUOUS CONDUCTION MODE**

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(52) **U.S. Cl.**
CPC ***H02M 1/4208*** (2013.01); ***H02M 3/33523*** (2013.01); ***H05B 33/0815*** (2013.01)

(58) **Field of Classification Search**
CPC H02M 1/4208; H02M 3/335; H05B 33/0815; H05B 37/02
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,790,878	A	2/1974	Brokaw
4,677,366	A	6/1987	Wilkinson et al.
4,683,529	A	7/1987	Bucher
4,737,658	A	4/1988	Kronmuller et al.
4,739,462	A	4/1988	Farnsworth et al.
4,937,728	A	6/1990	Leonardi
4,940,929	A	7/1990	Williams
4,977,366	A	12/1990	Powell
5,001,620	A	3/1991	Smith
5,003,454	A	3/1991	Bruning
5,055,746	A	10/1991	Hu et al.
5,109,185	A	4/1992	Ball
5,173,643	A	12/1992	Sullivan et al.
5,264,780	A	11/1993	Bruer et al.
5,278,490	A	1/1994	Smedley
5,383,109	A	1/1995	Maksimovic et al.
5,424,932	A	6/1995	Inou et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP	0536535 A1	4/1993
EP	0636889 A1	1/1995

(Continued)

OTHER PUBLICATIONS

Su, et al, Ultra Fast Fixed-Frequency Hysteretic Buck Converter with Maximum Charging Current Control and Adaptive Delay Compensation for DVS Applications, IEEE Journal of Solid-State Circuits, vol. 43, No. 4, Apr. 2008, pp. 815-822, Hong Kong University of Science and Technology, Hong Kong, China.

(Continued)

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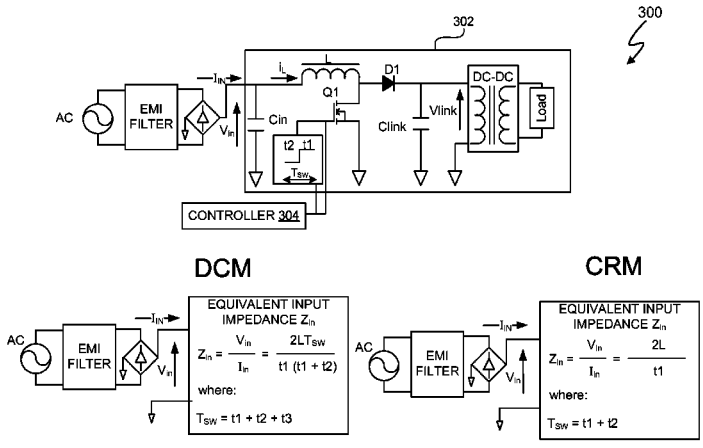
(57) **ABSTRACT**

A power system includes a controller to control a switching power converter, and the controller is configured to automatically transition operation of the switching power converter, during each cycle of an input voltage to the switching power converter, between operating in discontinuous conduction mode and critical conduction mode.

14 Claims, 7 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

5,430,635	A	7/1995	Liu
5,479,333	A	12/1995	McCambridge et al.
5,481,178	A	1/1996	Wilcox et al.
5,565,761	A	10/1996	Hwang
5,638,265	A	6/1997	Gabor
5,691,890	A	11/1997	Hyde
5,747,977	A	5/1998	Hwang
5,757,635	A	5/1998	Seong
5,764,039	A	6/1998	Choi et al.
5,783,909	A	7/1998	Hochstein
5,798,635	A	8/1998	Hwang et al.
5,808,453	A	9/1998	Lee
5,874,725	A	2/1999	Yamaguchi
5,960,207	A	9/1999	Brown
5,994,885	A	11/1999	Wilcox et al.
6,043,633	A	3/2000	Lev et al.
6,084,450	A	7/2000	Smith et al.
6,091,233	A	7/2000	Hwang et al.
6,160,724	A	12/2000	Hemena et al.
6,229,292	B1	5/2001	Redl et al.
6,259,614	B1	7/2001	Ribarich et al.
6,300,723	B1	10/2001	Wang et al.
6,304,066	B1	10/2001	Wilcox et al.
6,304,473	B1	10/2001	Telefus et al.
6,343,026	B1	1/2002	Perry
6,356,040	B1	3/2002	Preis et al.
6,445,600	B2	9/2002	Ben-Yaakov
6,469,484	B2	10/2002	L'Hermite et al.
6,510,995	B2	1/2003	Muthu et al.
6,531,854	B2	3/2003	Hwang
6,580,258	B2	6/2003	Wilcox et al.
6,583,550	B2	6/2003	Itwasa
6,628,106	B1	9/2003	Batarseh et al.
6,657,417	B1	12/2003	Hwang
6,696,803	B2	2/2004	Tao et al.
6,724,174	B1	4/2004	Esteves et al.
6,768,655	B1	7/2004	Yang et al.
6,781,351	B2	8/2004	Mednik et al.
6,839,247	B1	1/2005	Yang
6,882,552	B2	4/2005	Telefus et al.
6,894,471	B2	5/2005	Corva et al.
6,933,706	B2	8/2005	Shih
6,940,733	B2	9/2005	Schie et al.
6,944,034	B1	9/2005	Shteynberg et al.
6,956,750	B1	10/2005	Eason et al.
6,975,523	B2	12/2005	Kim et al.
6,980,446	B2	12/2005	Simada et al.
7,072,191	B2	7/2006	Nakao et al.
7,099,163	B1	8/2006	Ying
7,161,816	B2	1/2007	Shteynberg et al.
7,221,130	B2	5/2007	Ribeiro et al.
7,233,135	B2	6/2007	Noma et al.
7,266,001	B1	9/2007	Notohamiprodjo et al.
7,292,013	B1	11/2007	Chen et al.
7,295,452	B1	11/2007	Liu
7,411,379	B2	8/2008	Chu
7,554,473	B2	6/2009	Melanson
7,606,532	B2	10/2009	Wuidart
7,667,986	B2	2/2010	Artusi et al.
7,684,223	B2	3/2010	Wei
7,719,246	B2	5/2010	Melanson
7,719,248	B1	5/2010	Melanson
7,746,043	B2	6/2010	Melanson
7,804,480	B2	9/2010	Jeon et al.
7,834,553	B2	11/2010	Hunt et al.
7,872,883	B1	1/2011	Elbanhawy
7,894,216	B2	2/2011	Melanson
8,008,898	B2	8/2011	Melanson et al.
8,169,806	B2	5/2012	Sims et al.
8,193,717	B2	6/2012	Leiderman
8,222,772	B1	7/2012	Vinciarelli
8,242,764	B2	8/2012	Shimizu et al.
8,369,109	B2	2/2013	Niedermeier et al.
8,441,210	B2	5/2013	Shteynberg et al.
8,536,799	B1	9/2013	Grisamore et al.
8,610,364	B2	12/2013	Melanson et al.
8,803,439	B2	8/2014	Stamm et al.
8,816,593	B2	8/2014	Lys et al.
2003/0090252	A1	5/2003	Hazucha
2003/0111969	A1	6/2003	Konishi et al.
2003/0160576	A1	8/2003	Suzuki
2003/0174520	A1	9/2003	Bimbaud
2003/0214821	A1	11/2003	Giannopoulos et al.
2003/0223255	A1	12/2003	Ben-Yaakov
2004/0046683	A1	3/2004	Mitamura et al.
2004/0196672	A1	10/2004	Amei
2005/0057237	A1	3/2005	Clavel
2005/0207190	A1	9/2005	Gritter
2005/0231183	A1	10/2005	Li et al.
2005/0270813	A1	12/2005	Zhang et al.
2005/0275354	A1	12/2005	Hausman
2006/0013026	A1	1/2006	Frank et al.
2006/0022648	A1	2/2006	Zeltser
2006/0214603	A1	9/2006	Oh et al.
2007/0103949	A1	5/2007	Tsuruya
2008/0018261	A1	1/2008	Kastner
2008/0043504	A1	2/2008	Ye
2008/0062584	A1	3/2008	Freitag et al.
2008/0062586	A1	3/2008	Apfel
2008/0117656	A1	5/2008	Clarkin
2008/0130336	A1	6/2008	Taguchi
2008/0175029	A1	7/2008	Jung et al.
2008/0259655	A1	10/2008	Wei et al.
2008/0278132	A1	11/2008	Kesterson et al.
2008/0310194	A1	12/2008	Huang et al.
2009/0059632	A1	3/2009	Li et al.
2009/0067204	A1	3/2009	Ye et al.
2009/0108677	A1	4/2009	Walter et al.
2009/0184665	A1	7/2009	Femo
2009/0243582	A1	10/2009	Irissou et al.
2009/0295300	A1	12/2009	King
2010/0128501	A1	5/2010	Huang et al.
2010/0238689	A1	9/2010	Fei et al.
2010/0244793	A1	9/2010	Caldwell
2011/0110132	A1	5/2011	Rausch
2011/0199793	A1	8/2011	Kuang et al.
2011/0276938	A1	11/2011	Perry et al.
2011/0291583	A1	12/2011	Shen
2011/0309760	A1	12/2011	Beland et al.
2012/0056551	A1	3/2012	Zhu et al.
2012/0146540	A1	6/2012	Khayat et al.
2012/0153858	A1*	6/2012	Melanson et al. 315/279
2012/0187997	A1	7/2012	Liao et al.
2012/0248998	A1	10/2012	Yoshinaga
2012/0320640	A1	12/2012	Baurle et al.
2013/0181635	A1	7/2013	Ling
2014/0218978	A1	8/2014	Heuken et al.

FOREIGN PATENT DOCUMENTS

EP	1213823	A2	6/2002
EP	1289107	A3	8/2002
EP	1962263	A2	8/2008
EP	2232949		9/2010
EP	2257124	A1	12/2010
JP	2008053181	A	3/2006
WO	01/84697	A2	11/2001
WO	2004/051834	A1	6/2004
WO	20060013557	A1	2/2006
WO	2006/022107	A1	3/2006
WO	2007016373	A3	2/2007
WO	2008/004008	A2	1/2008
WO	20080152838	A2	12/2008
WO	2010011971	A1	1/2010
WO	2010065598	A2	6/2010
WO	2011008635	A1	1/2011

OTHER PUBLICATIONS

Wong, et al, "Steady State Analysis of Hysteretic Control Buck Converters", 2008 13th International Power Electronics and Motion Control Conference (EPE-PEMC 2008), pp. 400-404, 2008, National Semiconductor Corporation, Power Management Design Center, Hong Kong, China.

(56) **References Cited**

OTHER PUBLICATIONS

Zhao, et al, Steady-State and Dynamic Analysis of a Buck Converter Using a Hysteretic PWM Control, 2004 35th Annual IEEE Power Electronics Specialists Conference, pp. 3654-3658, Department of Electrical & Electronic Engineering, Oita University, 2004, Oita, Japan.

Texas Instruments, High Performance Power Factor Preregulator, UC2855A/B and UC3855A/B, SLUS328B, Jun. 1998, Revised Oct. 2005, pp. 1-14, Dallas, TX, USA.

Balogh, Laszlo, et al,Power-Factor Correction with Interleaved Boost Converters in Continuous-Inductr-Current Mode, 1993, IEEE, pp. 168-174, Switzerland.

Cheng, Hung L., et al, A Novel Single-Stage High-Power-Factor Electronic Ballast with Symmetrical Topology, Power Electronics and Motion Control Conference, 2006. IPEMC 2006. CES/IEEE 5th International, Aug. 14-16, 2006, vol. 50, No. 4, Aug. 2003, pp. 759-766, Nat. Ilan Univ., Taiwan.

Fairchild Semiconductor, Theory and Application of the ML4821 Average Current Mode PFC Controllerr, Fairchild Semiconductor Application Note 42030, Rev. 1.0, Oct. 25, 2000, pp. 1-19, San Jose, California, USA.

Garcia, O., et al, High Efficiency PFC Converter to Meet EN610000302 and A14, Industrial Electronics, 2002. ISIE 2002. Proceedings of the 2002 IEEE International Symposium, vol. 3, pp. 975-980, Div. de Ingenieria Electronica, Univ. Politecnica de Madrid, Spain.

Infineon Technologies AG, Standalone Power Factor Correction (PFC) Controller in Continuous Conduction Mode (CCM), Infineon Power Management and Supply, CCM-PFC, ICE2PCS01, ICE2PCS01G, Version 2.1, Feb. 6, 2007, p. 1-22, Munchen, Germany.

Lu, et al, Bridgeless PFC Implementation Using One Cycle Control Technique, International Rectifier, 2005, pp. 1-6, Blacksburg, VA, USA.

Brown, et al, PFC Converter Design with IR1150 One Cycle Control IC, International Rectifier, Application Note AN-1077, pp. 1-18, El Segundo CA, USA.

International Rectifer, PFC One Cycle Control PFC IC, International Rectifier, Data Sheet No. PD60230 rev. C, IR1150(S)(PbF), IR11501(S)(PbF), Feb. 5, 2007, pp. 1-16, El Segundo, CA, USA.

International Rectifier, IRAC1150=300W Demo Board, User's Guide, Rev 3.0, International Rectifier Computing and Communications SBU—AC-DC Application Group, pp. 1-18, Aug. 2, 2005, El Segundo, CO USA.

Lai, Z., et al, A Family of Power-Factor-Correction Controller, Applied Power Electronics Conference and Exposition, 1997. APEC '97 Conference Proceedings 1997., Twelfth Annual, vol. 1, pp. 66-73, Feb. 23-27, 1997, Irvine, CA.

Lee, P, et al, Steady-State Analysis of an Interleaved Boost Converter with Coupled Inductors, IEEE Transactions on Industrial Electronics, vol. 47, No. 4, Aug. 2000, pp. 787-795, Hung Hom, Kowloon, Hong Kong.

Linear Technology, Single Switch PWM Controller with Auxiliary Boost Converter, Linear Technology Corporation, Data Sheet LT1950, pp. 1-20, Milpitas, CA, USA.

Linear Technology, Power Factor Controller, Linear Technology Corporation, Data Sheet LT1248, pp. 1-12, Milpitas, CA, USA.

Supertex, Inc., HV9931 Unity Power Factor LED Lamp Driver, Supertex, Inc., Application Note AN-H52, 2007, pp. 1-20, Sunnyvale, CA, USA.

Ben-Yaakov, et al, The Dynamics of a PWM Boost Converter with Resistive Input, IEEE Transactions on Industrial Electronics, vol. 46., No. 3, Jun. 1999, pp. 1-8, Negev, Beer-Sheva, Israel.

Erickson, Robert W., et al, Fundamentals of Power Electronics, Second Edition, Chapter 6, 2001, pp. 131-184, Boulder CO, USA.

STMicroelectronics, CFL/TL Ballast Driver Preheat and Dimming L6574, Sep. 2003, pp. 1-10, Geneva, Switzerland.

Fairchild Semiconductor, 500W Power-Factor-Corrected (PFC) Converter Design with FAN4810, Application Note 6004, Rev. 1.0.1, Oct. 31, 2003, pp., 1-14, San Jose, CA, USA.

Fairfield Semiconductor, Power Factor Correction (PFC) Basics, Application Note 42047, Rev. 0.9.0, Aug. 19, 2004, pp. 1-11, San Jose, CA, USA.

Fairchild Semiconductor, Design of Power Factor Correction Circuit Using FAN7527B, Application Note AN4121, Rev. 1.0.1, May 30, 2002, pp. 1-12, San Jose, CA, USA.

Fairchild Semiconductor, Low Start-Up Current PFC/PWM Controller Combos FAN4800, Rev. 1.0.6, Nov. 2006, pp. 1-20, San Jose, CA, USA.

Prodic, Aleksander, Compensator Design and Stability Assessment for Fast Voltage Loops of Power Factor Correction Rectifiers, IEEE Transactions on Power Electronics, vol. 22, Issue 5, Sep. 2007, pp. 1719-1730, Toronto, Canada.

Fairchild Semiconductor, ZVS Average Current PFC Controller Fan 4822, Rev. 1.0.1, Aug. 10, 2001, pp. 1-10, San Jose, CA, USA.

Prodic, et al, Dead-Zone Digital Controller for Improved Dynamic Response of Power Factor Preregulators, Applied Power Electronics Conference and Exposition, 2003, vol. 1, pp. 382-388, Boulder CA, USA.

Philips Semiconductors, 90W Resonant SMPS with TEA1610 Swing Chip, Application Note AN99011, Sep. 14, 1999, pp. 1-28, The Netherlands.

STMicroelectronics, Advanced Transition-Mode PFC Controller L6563 and L6563A, Mar. 2007, pp. 1-40, Geneva, Switzerland.

ON Semiconductor, Power Factor Controller for Compact and Robust, Continuous Conduction Mode Pre-Converters, NCP1654, Mar. 2007, Rev. PO, pp. 1-10, Denver, CO, USA.

Fairchild Semicondctor, Simple Ballast Controller, KA7541, Rev. 1.0.3, Sep. 27, 2001, pp. 1-14, San Jose, CA, USA.

Fairchild Semiconductor, Power Factor Controller, ML4812, Rev. 1.0.4, May 31, 2001, pp. 1-18, San Jose, CA, USA.

Prodic, et al, Digital Controller for High-Frequency Rectifiers with Power Factor Correction Suitable for On-Chip Implementation, Power Conversion Conference—Nagoya, 2007. PCC '07, Apr. 2-5, 2007, pp. 1527-1531, Toronto, Canada.

Freescale Semiconductor, Dimmable Light Ballast with Power Factor Correction, Designer Reference Manual, DRM067, Rev. 1, Dec. 2005, M68HC08 Microcontrollers, pp. 1-72, Chandler, AZ, USA.

Freescale Semiconductor, Design of Indirect Power Factor Correction Using 56F800/E, Freescale Semiconductor Application Note, AN1965, Rev. 1, Jul. 2005, pp. 1-20, Chandler, AZ, USA.

Freescale Semiconductor, Implementing PFC Average Current Mode Control using the MC9S12E128, Application Note AN3052, Addendum to Reference Design Manual DRM064, Rev. 0, Nov. 2005, pp. 1-8, Chandler, AZ, USA.

Hirota, et al, Analysis of Single Switch Delta-Sigma Modulated Pulse Space Modulation PFC Converter Effectively Using Switching Power Device, Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual, vol. 2, pp. 682-686, Hyogo Japan.

Madigan, et al, Integrated High-Quality Rectifier-Regulators, Industrial Electronics, IEEE Transactions, vol. 46, Issue 4, pp. 749-758, Aug. 1999, Cary, NC, USA.

Renesas, Renesas Technology Releases Industry's First Critical-Conduction-Mode Power Factor Correction Control IC Implementing Interleaved Operations, R2A20112, pp. 1-4, Dec. 18, 2006, Tokyo, Japan.

Renesas, PFC Control IC R2A20111 Evaluation Board, Application Note R2A20111 EVB, all pages, Feb. 2007, Rev. 1.0, pp. 1-39, Tokyo, Japan.

Miwa, et al, High Efficiency Power Factor Correction Using Interleaving Techniques, Applied Power Electronics Conference and Exposition, 1992. APEC '92. Conference Proceedings 1992., Seventh Annual, Feb. 23-27, 1992, pp. 557-568, MIT, Cambridge, MA, USA.

Noon, Jim, High Performance Power Factor Preregulator UC3855A/B, Texas Instruments Application Report, SLUA146A, May 1996—Revised Apr. 2004, pp. 1-35, Dallas TX, USA.

NXP Semiconductors, TEA1750, GreenChip III SMPS Control IC Product Data Sheet, Rev.01, Apr. 6, 2007, pp. 1-29, Eindhoven, The Netherlands.

Turchi, Joel, Power Factor Correction Stages Operating in Critical Conduction Mode, ON Semiconductor, Application Note AND8123/D, Sep. 2003—Rev. 1 , pp. 1-20, Denver, CO, USA.

(56) **References Cited**

OTHER PUBLICATIONS

ON Semiconductor, GreenLine Compact Power Factor Controller: Innovative Circuit for Cost Effective Solutions, MC33260, Semiconductor Components Industries, Sep. 2005—Rev. 9, pp. 1-22, Denver, CO, USA.

ON Semiconductor, Enhanced, High Voltage and Efficient Standby Mode, Power Factor Controller, NCP1605, Feb. 2007, Rev. 1, pp. 1-32, Denver, CO, USA.

ON Semiconductor, Cost Effective Power Factor Controller, NCP1606, Mar. 2007, Rev. 3, pp. 1-22, Denver, CO, USA.

Renesas, Power Factor Correction Controller IC, HA16174P/FP, Rev. 1.0, Jan. 6, 2006, pp. 1-38, Tokyo, Japan.

Seidel, et al, A Practical Comparison Among High-Power-Factor Electronic Ballasts with Similar Ideas, IEEE Transactions on Industry Applications, vol. 41, No. 6, Nov./Dec. 2005, pp. 1574-1583, Santa Maria, Brazil.

STMicroelectronics, Electronic Ballast with PFC using L6574 and L6561, Application Note AN993, May 2004, pp. 1-20, Geneva, Switzerland.

Maksimovic, et al, Impact of Digital Control in Power Electronics, International Symposium on Power Semiconductor Devices and ICS, 2004, pp. 2-22, Boulder, Colorado, USA.

Fairchild Semiconductor, Ballast Control IC, FAN 7711, Rev. 1.0.3, 2007, pp. 1-23, San Jose,California, USA.

Yao, Gang et al, Soft Switching Circuit for Interleaved Boost Converters, IEEE Transactions on Power Electronics, vol. 22, No. 1, Jan. 2007, pp. 1-8, Hangzhou China.

STMicroelectronics, Transition Mode PFC Controller, Datasheet L6562, Rev. 8, Nov. 2005, pp. 1-16, Geneva, Switzerland.

Zhang, Wanfeng et al, A New Duty Cycle Control Strategy for Power Factor Correction and FPGA Implementation, IEEE Transactions on Power Electronics, vol. 21, No. 6, Nov. 2006, pp. 1-10, Kingston, Ontario, Canada.

STMicroelectronics, Power Factor Connector L6561, Rev 16, Jun. 2004, pp. 1-13, Geneva, Switzerland.

Texas Instruments, Avoiding Audible Noise at Light Loads when Using Leading Edge Triggered PFC Converters, Application Report SLUA309A, Mar. 2004—Revised Sep. 2004, pp. 1-4, Dallas, Texas, USA.

Texas Instruments, Startup Current Transient of the Leading Edge Triggered PFC Controllers, Application Report SLUA321, Jul. 2004, pp. 1-4, Dallas, Texas, USA.

Texas Instruments, Current Sense Transformer Evaluation UCC3817, Application Report SLUA308, Feb. 2004, pp. 1-3, Dallas, Texas, USA.

Texas Instruments, BiCMOS Power Factor Preregulator Evaluation Board UCC3817, User's Guide, SLUU077C, Sep. 2000—Revised Nov. 2002, pp. 1-10, Dallas, Texas, USA.

Texas Instruments, Interleaving Continuous Conduction Mode PFC Controller, UCC28070, SLUS794C, Nov. 2007—Revised Jun. 2009, pp. 1-45, Dallas, Texas, USA.

Texas Instruments, 350-W Two-Phase Interleaved PFC Pre-regulator Design Review, Application Report SLUA369B, Feb. 2005—Revised Mar. 2007, pp. 1-22, Dallas, Texas, USA.

Texas Instruments, Average Current Mode Controlled Power Factor Correction Converter using TMS320LF2407A, Application Report SPRA902A, Jul. 2005, pp. 1-15, Dallas, Texas, USA.

Texas Instruments, Transition Mode PFC Controller, UCC28050, UCC28051, UCC38050, UCC38051, Application Note SLUS515D, Sep. 2002—Revised Jul. 2005, pp. 1-28, Dallas, Texas, USA.

Unitrode, High Power-Factor Preregulator, UC1852, UC2852, UC3852, Feb. 5, 2007, pp. 1-8, Merrimack, Maine, USA.

Unitrode, Optimizing Performance in UC3854 Power Factor Correction Applications, Design Note DN 39E, 1999, pp. 1-6, Merrimack, Maine, USA.

ON Semiconductor Four Key Steps to Design a Continuous Conduction Mode PFC Stage Using the NCP1653, Application Note AND8184/D, Nov. 2004, pp. 1-8, Phoenix, AZ, USA.

Unitrode, BiCMOS Power Factor Preregulator, Texas Instruments, UCC2817, UCC2818, UCC3817, UCC3818, SLUS3951, Feb. 2000—Revised Feb. 2006, pp. 1-25, Dallas, Texas, USA.

Unitrode, UC3854A/B and UC3855A/B Provide Power Limiting with Sinusoidal Input Current for PFC Front Ends, SLUA196A, Design Note DN-66, Jun. 1995—Revised Nov. 2001, pp. 1-6, Merrimack, Maine, USA.

Unitrode, Programmable Output Power Factor Preregulator, UCC2819, UCC3819, SLUS482B, Apr. 2001—Revised Dec. 2004, pp. 1-16, Merrimack, Maine, USA.

Texas Instruments, UCC281019, 8-Pin Continuous Conduction Mode (CCM) PFC Controller, SLU828B, Revised Apr. 2009, pp. 1-48, Dallas, Texas, USA.

http://toolbarpdf.com/docs/functions-and-features-of=inverters.html, Jan. 20, 2011, pp. 1-8.

Zhou, Jinghai, et al, Novel Sampling Algorithm for DSP Controlled 2kW PFC Converter, IEEE Transactions on Power Electronics, vol. 16, No. 2, Mar. 2001, pp. 1-6, Hangzhou, China.

Mammano, Bob, Current Sensing Solutions for Power Supply Designers, Texas Instruments, 2001, pp. 1-36, Dallas, Texas, USA.

Fairchild Semiconductor, Ballast Control IC FAN7532, Rev. 1.0.3, Jun. 2006, pp. 1-16, San Jose, California, USA.

Fairchild Semiconductor, Simple Ballast Controller, FAN7544, Rev. 1.0.0, Sep. 21, 2004, pp. 1-14, San Jose, California, USA.

* cited by examiner

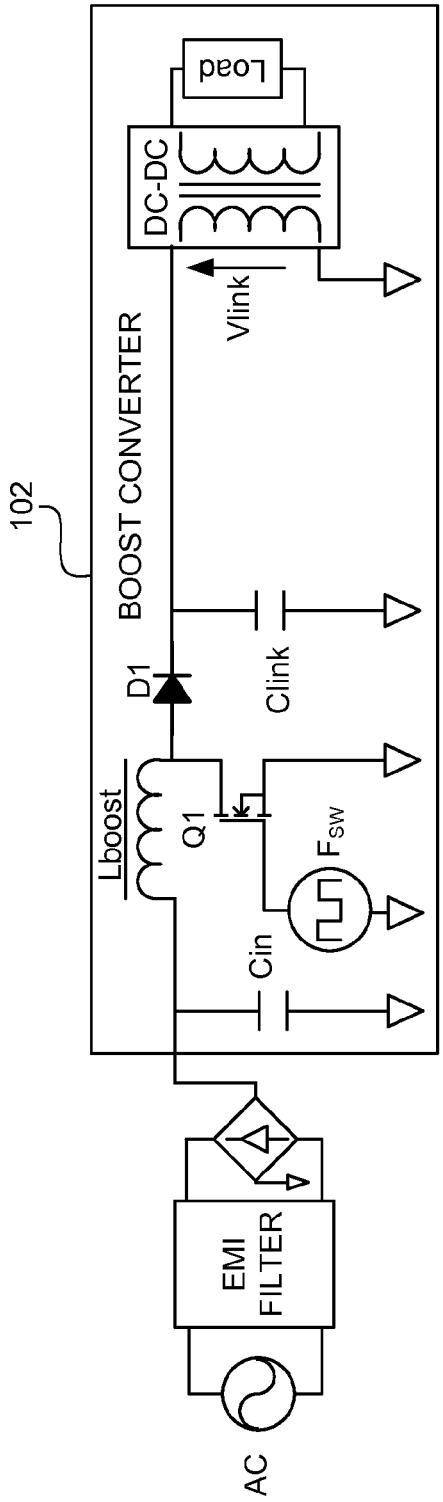


FIG. 1 (PRIOR ART)

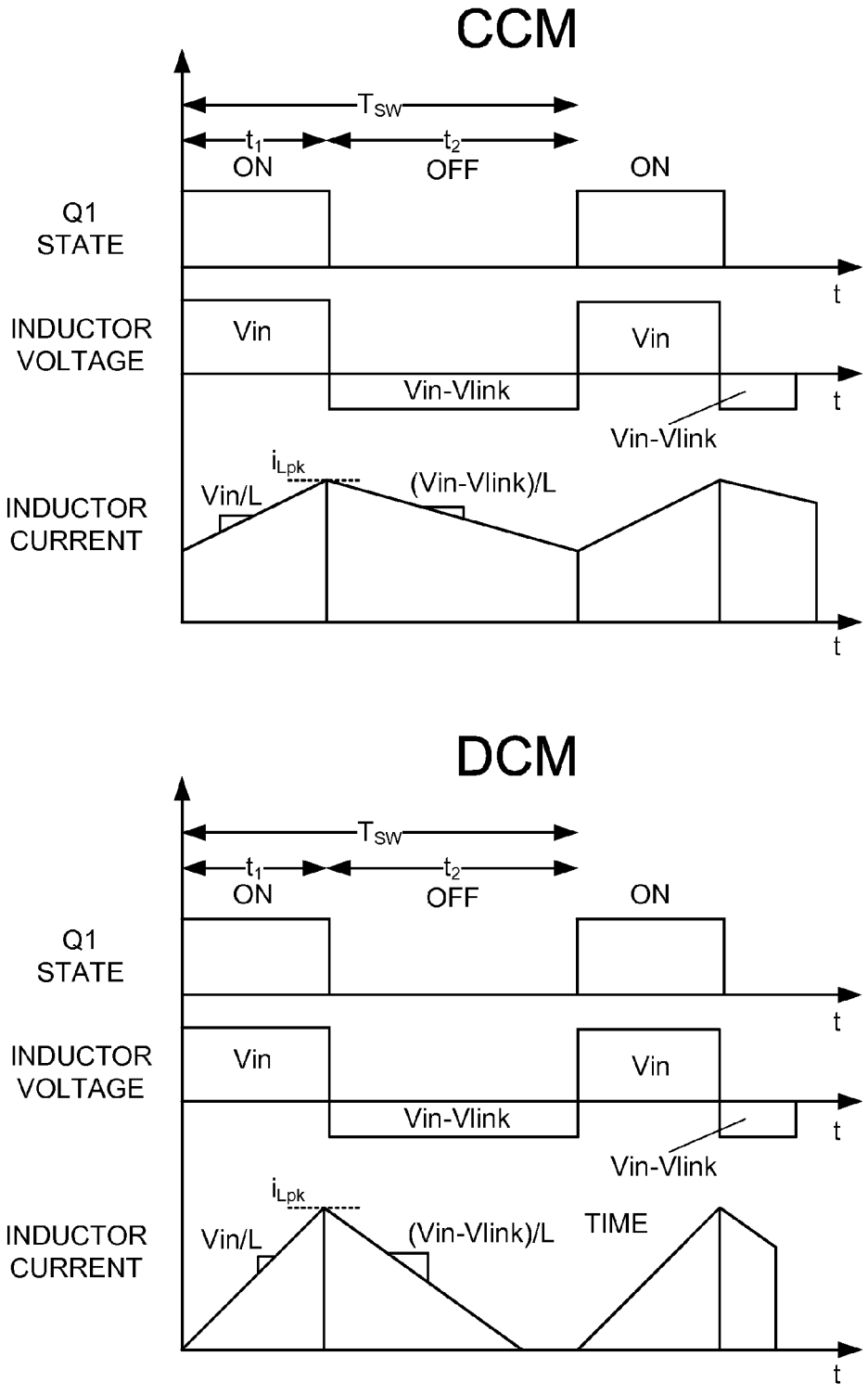


FIG. 2 (PRIOR ART)

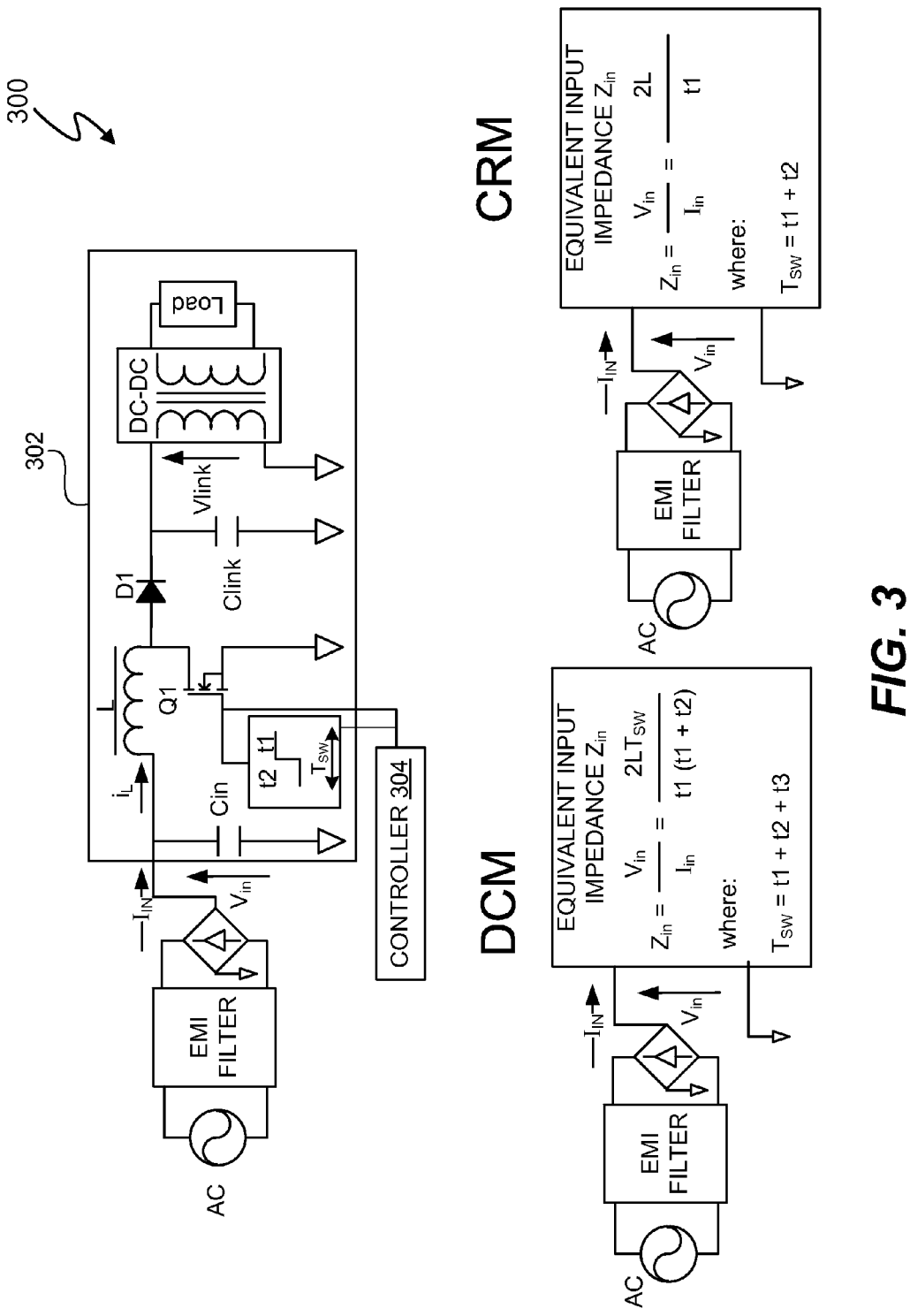

300
302
DC-DC
Load
Vlink
Clink
D1
Q1
L
i_L
Cin
t2
t1
T_{SW}
CONTROLLER 304
I_{IN}
V_{in}
EMI FILTER
AC
CRM
EQUIVALENT INPUT IMPEDANCE Z_{in}
$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{2L}{t1}$
where:
$T_{SW} = t1 + t2$
DCM
EQUIVALENT INPUT IMPEDANCE Z_{in}
$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{2LT_{SW}}{t1\ (t1 + t2)}$
where:
$T_{SW} = t1 + t2 + t3$

FIG. 3

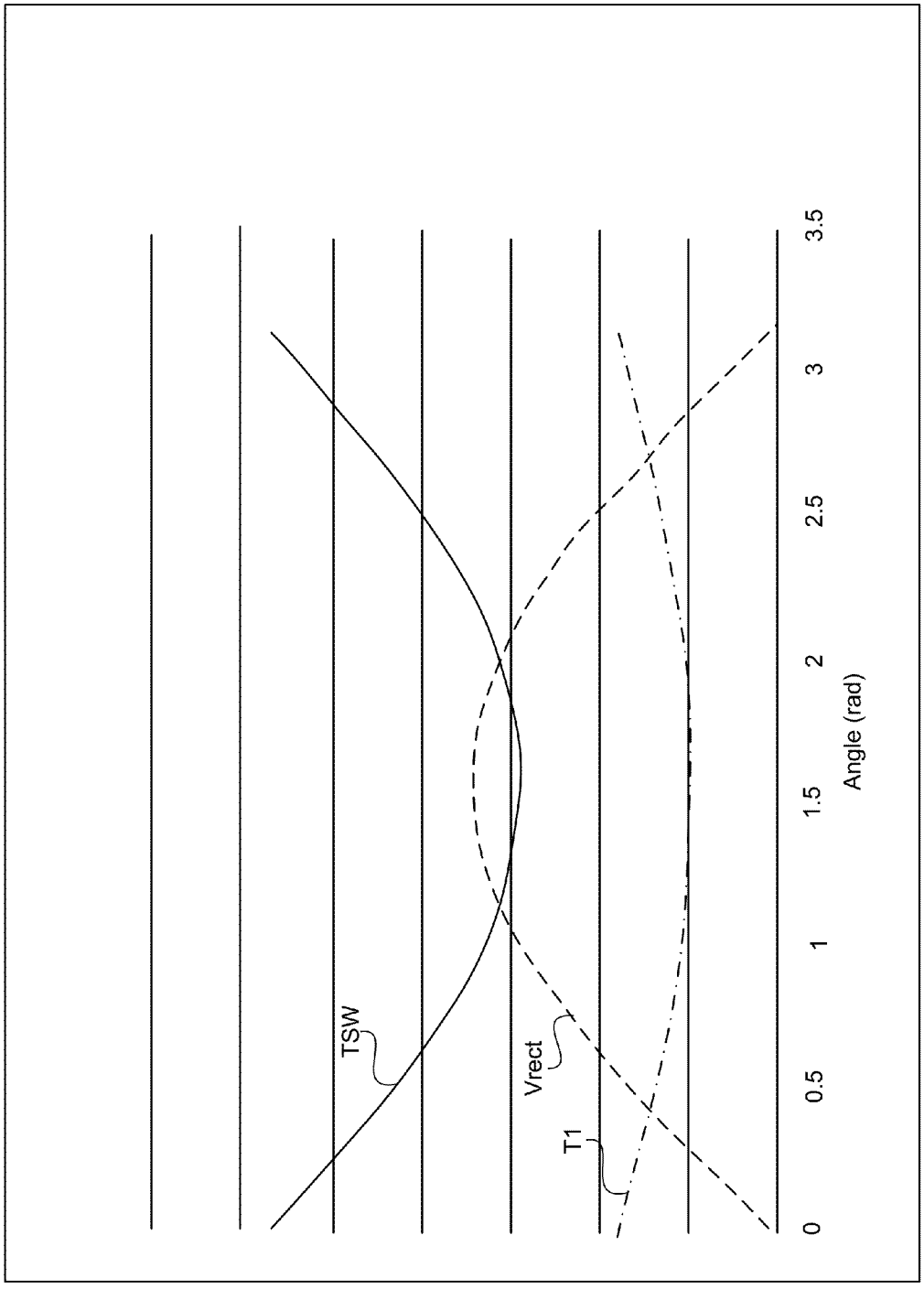


FIG. 4

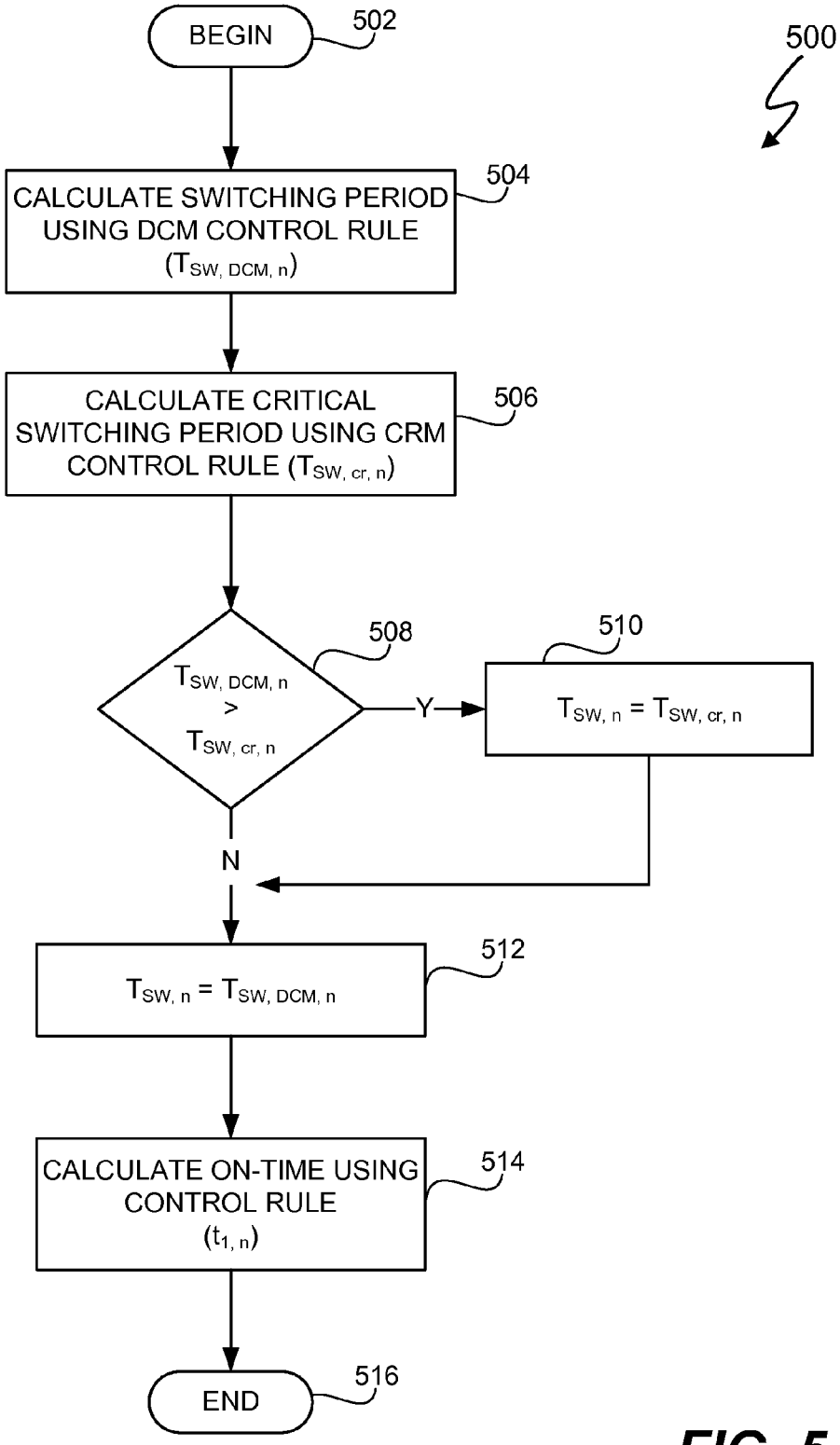

BEGIN
502
500
CALCULATE SWITCHING PERIOD USING DCM CONTROL RULE ($T_{SW, DCM, n}$)
504
CALCULATE CRITICAL SWITCHING PERIOD USING CRM CONTROL RULE ($T_{SW, cr, n}$)
506
$T_{SW, DCM, n}$ > $T_{SW, cr, n}$
508
Y
$T_{SW, n} = T_{SW, cr, n}$
510
N
$T_{SW, n} = T_{SW, DCM, n}$
512
CALCULATE ON-TIME USING CONTROL RULE ($t_{1, n}$)
514
END
516

FIG. 5

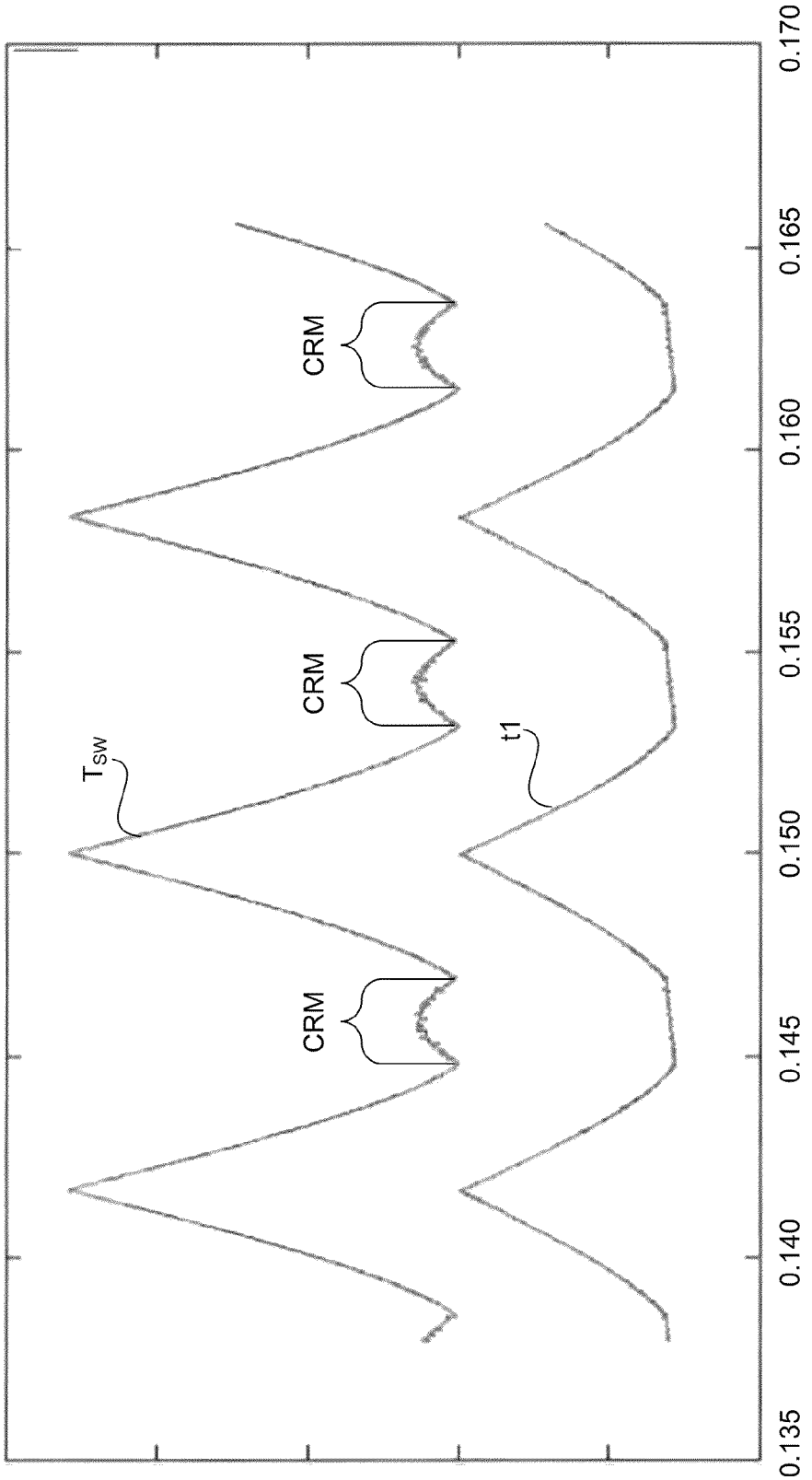

CRM
CRM
CRM
T_{SW}
t1
0.135
0.140
0.145
0.150
0.155
0.160
0.165
0.170
TIME

FIG. 6

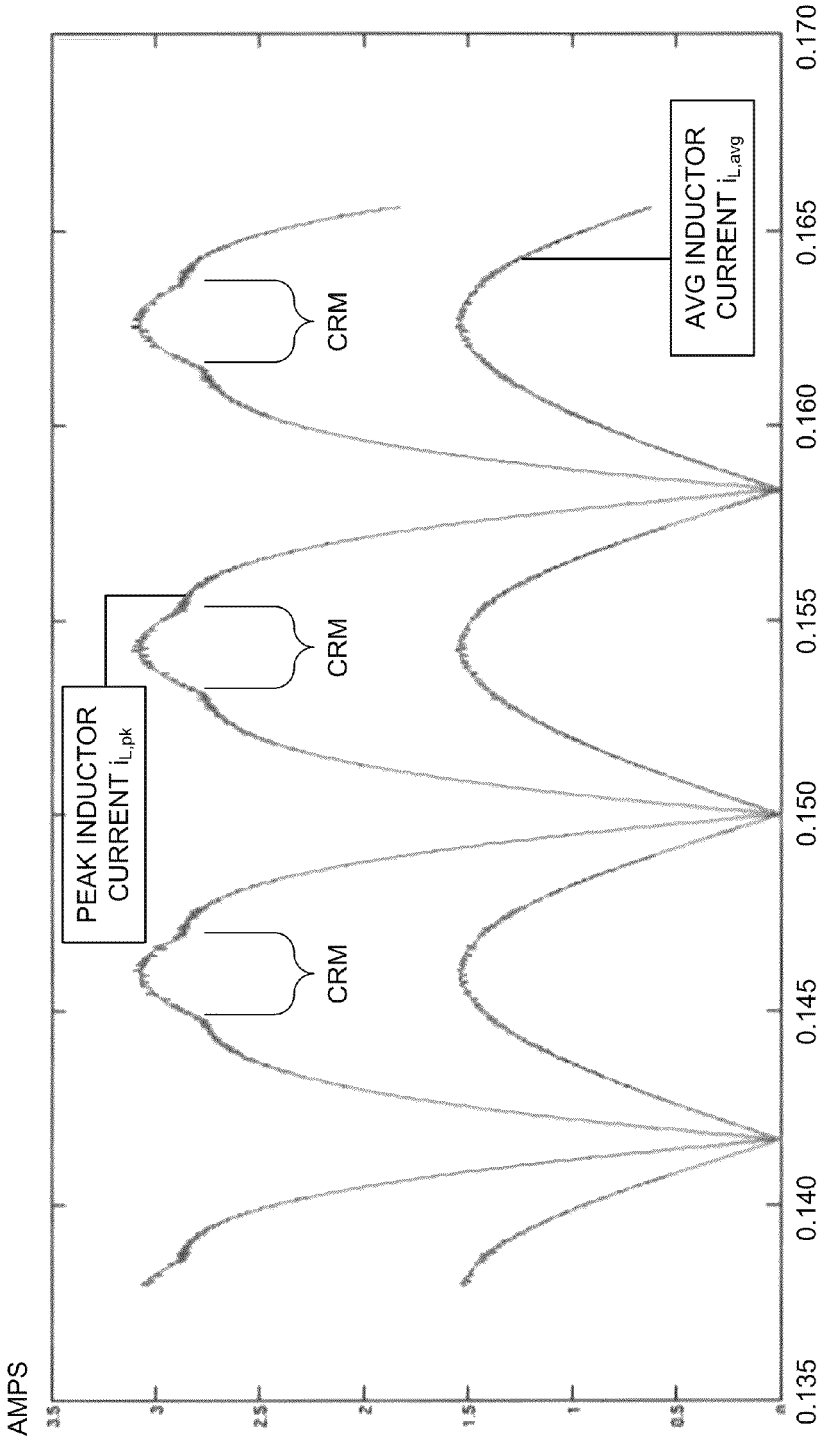

AMPS
TIME
PEAK INDUCTOR CURRENT $i_{L,pk}$
AVG INDUCTOR CURRENT $i_{L,avg}$
CRM
CRM
CRM
0.135
0.140
0.145
0.150
0.155
0.160
0.165
0.170

FIG. 7

CONTROLLING POWER FACTOR IN A SWITCHING POWER CONVERTER OPERATING IN DISCONTINUOUS CONDUCTION MODE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates in general to the field of electronics, and more specifically to a system and method for controlling power factor in a switching power converter operating in discontinuous conduction mode.

2. Description of the Related Art

Various standards bodies establish consumer product energy efficiency standards, such as power quality. Power Factor (PF) is one measure of power quality and represents a measure of how efficiently energy is drawn from an alternating current (AC) source. For example, the Energy Start 80 Plus Platinum standard specifies that products must exceed a power factor of 0.9 from 50% to 100% of maximum power load. Power supply designers often use active power factor correction (PFC) circuits to meet the PF requirements.

FIG. **1** depicts a boost-type switching power converter, which converts an input voltage from an AC voltage source into a boosted output voltage supplied of the load. The AC input voltage passes through an optional electro-magnetic interference (EMI) filter and then a rectifier. The rectified AC voltage is the input to the boost converter which includes the input and output capacitors (respectively, C_{in} and C_{link}), the complimentary switches (Q**1** and D**1**) and the inductor (L_{Boost}). The output voltage of the boost converter, VLink, is a DC regulated voltage that is commonly used as the input voltage to an isolated DC-DC converter stage.

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. When being charged, the inductor L_{Boost} accumulates energy, when being discharged the inductor L_{Boost} transfers the accumulated energy acting like a source. The voltage produced by the inductor L_{Boost} during the discharge phase is related to the rate of change of current and not to the original charging voltage, thus allowing different input and output voltages.

FET Q**1** is driven by a pulse width modulated signal, having a frequency of F_{SW}, applied at the gate of the FET Q**1**. In a charging phase, the FET Q**1** is ON, resulting in an increase in the inductor current (di=v/L·dt). In the discharging phase, the FET Q**1** is OFF and the only path for the inductor current is through the fly-back diode D**1**, the capacitor Clink and the load (DC-DC converter), which results in transferring the energy accumulated by the inductor L_{Boost} during the charging phase into the output capacitor Clink. The input current is the same as the inductor current.

FIG. **2** depicts representative waveforms associated with two different operating modes for the boost converter depending on the inductor current shape. If the current through the inductor L_{Boost} at the end of the discharging phase does not fall to zero, the boost converter operates in continuous mode (CCM); otherwise, the boost converter operates is discontinuous conduction mode (DCM).

The respective CCM and DCM control techniques have their advantages and disadvantages, however, for low power applications, less than 200-300 watts, DCM offers significant performances and efficiency benefits with simpler control algorithms.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may be better understood, and its numerous objects, features and advantages made apparent to those skilled in the art by referencing the accompanying drawings. The use of the same reference number throughout the several figures designates a like or similar element.

FIG. **1** depicts a boost-type switching power converter.

FIG. **2** depicts representative waveforms associated with two different operating modes for the boost converter of FIG. **1**.

FIG. **3** depicts an electronic system with a boost-type switching power converter.

FIG. **4** depicts an exemplary rectified input voltage, ON-TIME t**1**, and switching period T_{SW}.

FIG. **5** depicts a switching algorithm that calculates a pulse width t**1** and switching period T for the n^{th} switching cycle of a switch of the switching power converter of FIG. **3**.

FIGS. **6** and **7** depict DCM and CRM simulation results for a full load and minimum input voltage.

DETAILED DESCRIPTION

In at least one embodiment, a power system includes a controller to control a switching power converter, and the controller is configured to automatically transition operation of the switching power converter, during each cycle of an input voltage to the switching power converter, between operating in discontinuous conduction mode and critical conduction mode.

FIG. **3** depicts an electronic system **300** with a boost-type switching power converter. DCM & CRM Operation Mode:

The input filter capacitor Cin and EMI filter absorb the high-frequency component of the inductor current i_L, which makes the input current I_{in} a low frequency signal in DCM mode given by:

$$I_{in} = i_{L,avg} = i_{L,pk}\frac{t_1 + t_2}{2T_{SW}} \qquad \text{Equation 1}$$

where I_{in} is the input current to the switching power converter **300**, $i_{L,avg}$ is the average inductor current, $i_{L,pk}$ is the peak inductor current, t**1** is the ON TIME of the switch Q**1**, t**2** is the OFF TIME of the switch Q**1**, and T_{SW} is the switching period of the switch Q**1**. The input impedance Z_{in} in DCM mode is given by:

$$Z_{in} = \frac{V_{in}}{I_{in}} = V_{in}\frac{L}{V_{in}}\frac{2T_{SW}}{t_1(t_1 + t_2)} = \frac{2LT_{SW}}{t_1(t_1 + t_2)} \qquad \text{Equation 2a}$$

where:

$$i_{L,pk} = \frac{V_{in}}{L}t_1$$

where V_{in} is the input voltage to the switching power converter **300** and I_{in} is the input current to the switching power converter **300**. Power factor correction requires the boost controller to maintain the input impedance constant (or slowly varying). Making t**3** zero (where t**3** is the time from when the inductor current i_L stops flowing and when the next t**1** begins), which is a special case of DCM, simplifies eq. (2a):

$$T_{SW} = t_1 + t_2 \qquad \text{Equation 2b}$$

$$i_{L,pk} = \frac{V_{in}}{L}t_1$$

-continued

hence

$$I_{in} = \frac{V_{in}}{2L} t_1$$

$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{2L}{t_1}$$

This special DCM mode is called Critical Conduction Mode, CRM. CRM operates at the boundary between DCM and CCM mode.

As seen in eq. (2b), CRM control is very simple; PFC is achieved by simply keeping t**1** constant. Most of the conunercial DCM PFC controllers operate in CRM mode. NOTE: references to CRM mode means time t**3** equals 0. If time t**3** is non-zero, the switching power converter operates in DCM mode. DCM needs higher peak inductor current i_L comparing to CRM for the same power. Thus, CRM is generally preferred at around the sinusoidal peak but to avoid high switching frequencies DCM is preferred close to the line troughs.

Maximum Power

Regardless of the operational mode, to limit the maximum peak current to the same level as for a CRM controller, at minimum input voltage V_{IN}, min and maximum power demand Pmax, the controller operates the switching power converter in CRM mode at the peak of the line input voltage. Assuming a perfect power factor correction and 100% efficiency, the maximum power is given by:

$$P_{max} = \frac{1}{2} \frac{V^2_{in,min,rms}}{L f_{sw,max}} \left(\frac{V_{link}}{V_{link} - V_{in,min,pk}} \right) \quad \text{Equation 3}$$

Where V_{IN},min is the Minimum input voltage, •Vlink is the output voltage of the switching power converter, L is Boost Inductor inductance value. and fsw,max is the switching frequency $1/T_{SW}$ at the peak of the line input voltage.

The switching frequency is a constant and not generally accessible by a user of the controller, thus, the maximum power for a specific application is setup by the value of the boost inductor. Any positive variation on the inductor, due to manufacture tolerances and/or in the input line, due to demand peaks in the power distribution network, will limit the maximum power available. To compensate, the designers often oversize the inductor value L, sometimes by more than 40%, resulting in non-optimal operating conditions with performance degradation especially in efficiency and EMI compatibility.

In at least one embodiment, to solve the maximum power problem and maintain the same inductor peak current levels compared to a CRM solution, a switching algorithm, such as the switching algorithm **500** (FIG. **5**), controls the switching frequency of switch Q**1** in FIG. **3** and auto-adapts the switching frequency of switch Q**1** and operates the switching power converter **300** in, or close to, CRM mode (i.e. constant t**1** and variable switching frequency fsw) when the power demand by the load is larger than the power available in DCM mode. The next section describes the original and modified algorithm.

Original Algorithm Control Rules

For each switching cycle, the controller calculates:

The switching period Tsw, using the DCM switching period rule of Equation 4. The switching frequency basically follows the input line voltage profile; minimum at the trough and maximum at the peak of the line voltage.

The FET ON Time, t**1**, using the DCM ON-TIME control rule. The ON-TME includes 2 parts, slow (Equation 5) and fast (Equation 6) varying parts compared to the input line voltage period. The slow part (Equation 5), calculated twice per input line voltage period, includes the DC link voltage, RMS input voltage and load demand. The fast part (Equation 6), calculated once per switching period, includes instantaneous input/link voltages and calculated switching period.

$$T_{SW}(n) = TT_{min}\left(2 - \frac{v_{in}(n)}{V_{in,pk}}\right) \quad \text{Equation 4}$$

$$C_{halflinecycle} = TT_{min} \times \left(\frac{V_{in,pk,min}}{V_{in,pk}} \right)^2 \times \left(\frac{V_{link} - V_{in,pk,min}}{V^2_{link}} \right) \times P_u \quad \text{Equation 5}$$

$$t_1(n) = \sqrt{C_{halflinecycle} T_{SW}(n)(V_{link}(n) - v_{in}(n))} \quad \text{Equation 6}$$

FIG. **4** depicts an exemplary rectified input voltage, ON-TIME t**1**, and switching period T_{SW} for a specific input line and load configuration.

New Algorithm Control Rules

The relationship between ON-TIME, t**1** of switch Q**1** of FIG. **3**, and switching period, Tsw,cr in critical mode of switch Q**1** is given by:

$$T_{SW,cr} = t_1 \frac{V_{link}}{V_{link} - v_{in}} \quad \text{Equation 7}$$

An increase on the power demand increases the ON-TIME (Equation 6), which increases the critical switching period (Equation 7). The critical switching period is used if larger than the calculated DCM switching period (Equation 4). Using the larger period results in more power transferred (Equation 3). FIG. **5** depicts the switching algorithm **500** that calculates a pulse width t**1** and switching period T for the n^{th} switching cycle of switch Q**1** in FIG. **3**. For the cases where the critical switching period is selected, the ON-TIME $t_1(n)$ for the n^{th} cycle of the switch Q**1** is defined as:

$$t_1(n) = C_{halflinecycle} V_{link}(n) \quad \text{Equation 8)}$$

Because Vlink is a slow moving signal, the ON-TIME can be approximated to a constant which fills the power factor correction requirement. The new algorithm fulfills:

Auto adapts between CRM and DCM mode depending on power transfer requirements.

Performs power factor correction independent on operating mode.

The switching algorithm **500** begins at operation **502** and proceeds to operation **504**. Operation **504** calculates the n^{th} switching period using the DCM control rule ($T_{SW,DCM,n}$). Operation **506** calculates the n^{th} critical switching period using the CRM control rule ($T_{SW,cr,n}$). Operation **508** determines if the switching period using the DCM control rule $T_{SW,DCM,n}$ is greater than the switching period using the CRM control rule $T_{SW,cr,n}$. If the n^{th} switching period using the DCM control rule $T_{SW,DCM,n}$ is greater than the n^{th} switching period using the CRM control rule $T_{SW,cr,n}$, then operation

510 selects the n^{th} switching period $T_{SW,n}$ to equal the switching period $T_{SW,cr,n}$ calculated using the CRM control rule. If the n^{th} switching period using the DCM control rule $T_{SW,DCM,n}$ is less than the n^{th} switching period using the CRM control rule $T_{SW,cr,n}$, then operation **510** selects the n^{th} switching period $T_{SW,n}$ to equal the switching period $T_{SW,DCM,n}$ calculated using the DCM control rule. Operation **514** then calculates the on-time $t_{1,n}$ for the n^{th} switching period using the control rule associated with the switching period determined in operation **508**.

FIGS. **6** and **7** depict DCM and CRM simulation results for a full load and minimum input voltage. The boost inductor value L was increased by 20% to reduce available power. To deliver the requested power of 120% of maximum rated power near the peak of the line input voltage, the controller of FIG. **3** switches to CRM mode as indicated by an approximately constant t**1** and increased switching period T_{SW}. The inductor peak current $i_{L,pk}$ increases but the inductor average current $i_{L,avg}$ (i.e. input current) retains a sinusoidal shape.

Although embodiments have been described in detail, it should be understood that various changes, substitutions, and alterations can be made hereto without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. An apparatus comprising:

a controller to control a switching power converter, wherein the controller is configured to automatically transition operation of the switching power converter, during each cycle of an input voltage to the switching power converter, between operating in discontinuous conduction mode and critical conduction mode, wherein during each cycle of a control signal to a switch that controls power delivered to a load coupled to the switching power converter, to automatically transition operation of the switching power converter between operating in discontinuous conduction mode and critical conduction mode, the controller is configured to:

determine a first period of a control signal to a switch of the switching power converter in accordance with a discontinuous conduction mode control rule, wherein the switch controls power delivered to an output of the switching power converter;

determine a second period of the control signal in accordance with a critical conduction mode control rule;

compare the first period and the second period;

set an actual period of the control signal equal to the first period if the first period is less than the second period and set an actual period of the control signal equal to the second period if the first period is greater than the second period; and

calculate an ON time of the switch in accordance with one of: (i) the discontinuous conduction mode control rule if the actual period is set to the first period and (ii) the critical conduction mode control rule if the actual period is set to the second period.

2. The apparatus of claim **1** wherein the controller is further configured to operate the switching power converter in critical conduction mode when a determined switching period of the switch in the switching power converter that controls power delivered to the load of the switching power converter is more efficient than a determined switching period of the switch for operating the switching power converter in discontinuous conduction mode.

3. The apparatus of claim **1** further comprising:

the switching power converter coupled to the controller, and

the load coupled to the switching power converter.

4. The apparatus of claim **3** wherein the load comprises a light emitting diode.

5. A method comprising:

controlling a switching power converter to automatically transition operation of the switching power converter, during each cycle of an input voltage to the switching power converter, between operating in discontinuous conduction mode and critical conduction mode, wherein to automatically transition operation of the switching power converter, during each cycle of an input voltage to the switching power converter, between operating in discontinuous conduction mode and critical conduction mode comprises:

determining a first period of a control signal to a switch of the switching power converter in accordance with a discontinuous conduction mode control rule, wherein the switch controls power delivered to an output of the switching power converter;

determining a second period of the control signal in accordance with a critical conduction mode control rule;

comparing the first period and the second period;

setting an actual period of the control signal equal to the first period if the first period is less than the second period and set an actual period of the control signal equal to the second period if the first period is greater than the second period; and

calculating an ON time of the switch in accordance with one of: (i) the discontinuous conduction mode control rule if the actual period is set to the first period and (ii) the critical conduction mode control rule if the actual period is set to the second period.

6. The method of claim **5** wherein the method further comprises:

operating the switching power converter in critical conduction mode when a determined switching period of a switch in the switching power converter that controls power delivered to a load of the switching power converter is more efficient than a determined switching period of the switch for operating the switching power converter in discontinuous conduction mode.

7. The method of claim **5** further comprising:

providing power from the switching power converter to a load.

8. The method of claim **7** wherein the load comprises a light emitting diode.

9. A lighting system comprising:

a switching power converter, wherein the switching power converter include an inductor, a link capacitor coupled to the inductor, and a switch having a first terminal coupled between the inductor and the link capacitor;

a load coupled to the link capacitor, and

a controller coupled to a conduction control terminal of the switch, wherein the controller is configured to:

(a) determine a first period of a control signal for the switch in accordance with a discontinuous conduction mode control rule;

(b) determine a second period of the control signal for the switch in accordance with a critical conduction mode control rule;

(c) compare the first period and the second period;

(d) set an actual period of the control signal equal to the first period if the first period is less than the second

period and set an actual period of the control signal equal to the second period if the first period is greater than the second period;

(e) calculate an ON time of the switch in accordance with one of: (i) the discontinuous conduction mode control rule if the actual period is set to the first period and (ii) the critical conduction mode control rule if the actual period is set to the second period; and

(f) provide a control signal to the switch, wherein the control signal comprises a period equal to the actual period and a pulse width equal to the ON time calculated.

10. The lighting system of claim **9** wherein the load comprises one or more light emitting diodes.

11. The lighting system of claim **9** wherein the controller is configured to perform (a)-(f) for each cycle of the switch.

12. A method to control a switching power converter and provide power to a load, the method comprising:

(a) determining a first period of a control signal to a switch of the switching power converter in accordance with a discontinuous conduction mode control rule, wherein the switch controls power delivered to an output of the switching power converter;

(b) determining a second period of the control signal in accordance with a critical conduction mode control rule;

(c) comparing the first period and the second period;

(d) setting an actual period of the control signal equal to the first period if the first period is less than the second period and set an actual period of the control signal equal to the second period if the first period is greater than the second period;

(e) calculating an ON time of the switch in accordance with one of: (i) the discontinuous conduction mode control rule if the actual period is set to the first period and (ii) the critical conduction mode control rule if the actual period is set to the second period; and

(f) providing a control signal to the switch, wherein the control signal comprises a period equal to the actual period and a pulse width equal to the ON time calculated.

13. The method of claim **12** wherein the load comprises one or more light emitting diodes.

14. The method of claim **12** further comprising:

performing (a)-(f) for each cycle of the switch.

* * * * *